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TECHNICAL REPORT

PR-7

AN AUTOMATIC GUARD-RING TEMPERATURE CONTROLLER FOR THERMAL-CONDUCTIVITY MEASUREMENTS

QUARTERMASTER RESEARCH & ENGINEERING CENTER

PIONEERING RESEARCH DIVISION

OCTOBER 1962 NATICK, MASSACHUSETTS

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3. Automatic control
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7. Proportional control
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Michael J. Sacco* Francis W. Botsch*
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Project Reference:
7X99-25-001

October 1962

FOREWORD

This is the second of three reports which describe work in the field of thermal conductivity performed jointly by the Pioneering Research Division and the former Environmental Protection Research Division of this Center. Most of the work described in this report was performed by the Biophysics Branch of EPRD. It was supported in part by funds made available through the Thermalibrium Suit program. The other two reports of the group are listed as references at the end of this report.

S. DAVID BAILEY, Ph. D.
Director
Pioneering Research Division

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CONTENTS

ABSTRACT

An automatic controller is described, which maintains the guard ring at the same temperature as the hot plate in an apparatus for measuring thermal conductivity. Control is maintained in response to the signal from a 6-power thermopile, which actuates a commercial electronic null detector. The output of the null detector drives a commercial magnetic amplifier. Proportional control is obtained by superposing an oscillating signal, generated by a Wien-bridge oscillator, on the control signal, so that the control relay continually opens and closes with a period of about 5 seconds. An increase in the demand for power causes the "closed" intervals to become longer and the "open" intervals to become shorter. Opening or closing of the relay changes the power input by only about 2 percent when conditions suitable for making measurements exist. Temperature control to within ± 2 mdeg C can be achieved under favorable conditions.

AN AUTOMATIC GUARD-RING TEMPERATURE CONTROLLER FOR THERMAL-CONDUCTIVITY MEASUREMENTS

1. Introduction

The automatic control device described in this report is shown in Figure 1, which shows the thermal-conductivity apparatus and all the associated measuring and control equipment. The principal items of automatic control equipment are the two units seated on the top of the right-hand side of the relay rack.

The automatic control device maintains the guard ring of the thermal-conductivity apparatus at the same temperature as the hot plate, so that there will be no lateral heat flow from the hot plate. A thermopile with 6 junctions on the hot plate and 6 junctions on the guard ring indicates any inequality of temperature between the two parts. The emf of the thermopile is applied to a Brown (Honeywell) null detector. In the null detector the thermocouple emf is chopped, amplified, detected, and passed through a zero-center indicating meter.

The automatic control device receives the output of the null detector, and in response adjusts the power supplied to the guard ring. The principle of operating the control is described in the next section.

Manual controls are provided, in addition to the automatic control. At the beginning of a run it is usually convenient, for a short time at least, to use manual control. The manual controls are also needed when large adjustments in power, outside the desired range of the automatic control, are required.

Information regarding our thermal-conductivity apparatus but not dealing primarily with automatic control will be found in reference (1). The results of an experimental program in which the apparatus was used are given in reference (2).

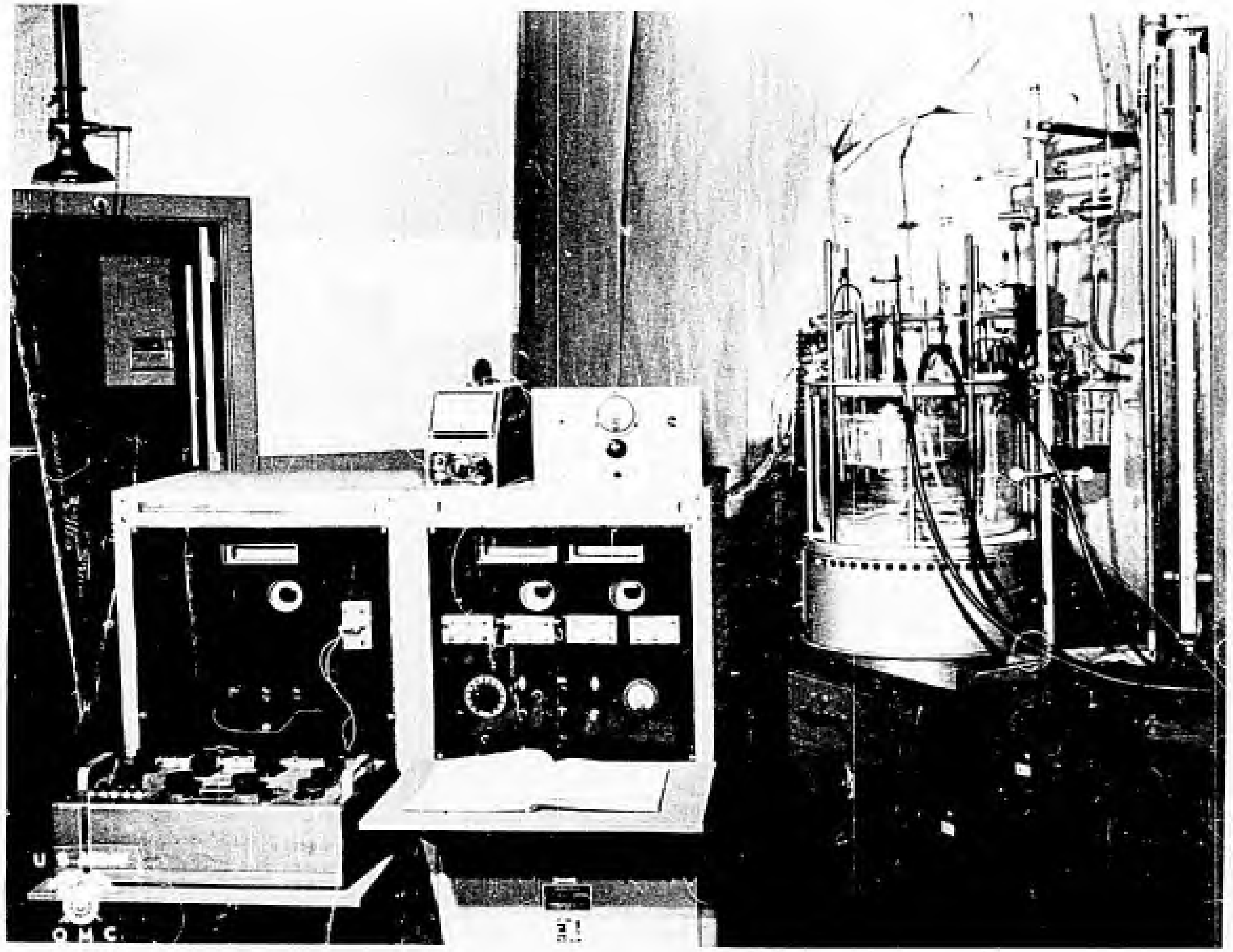

Figure 1. Photograph of thermal-conductivity apparatus. The automatic control equipment sits on the top of the relay rack.

2. Principle of Temperature Control

The simplest type of temperature control is the on-off type, in which excess heat is supplied until such time as the sensor signifies that the temperature is too high. At this time the heat is entirely cut off and the system cools. When the sensor indicates that the system is too cold, full heat is turned on and the temperature of the system again rises. With such a system, if the power supplied is double that required to maintain the desired temperature, then the power is on for 50 percent of the time. That is, the power supplied times the fraction of the time the power is on equals the power required.

Such a system tends to overshoot, because of the time delay in the flow of heat from the heater to the sensor. The power remains on until the sensor reaches the desired temperature and is then cut off, but by this time an excess of heat has been supplied and the temperature at the sensor overshoots. The sensor does not call for heat again until the temperature has fallen to the desired value, but when this point is reached there is a deficiency of heat in the system and the temperature "undershoots". The oscillations of temperature continue indefinitely.

Continued oscillations will exist in any temperature-control system in which the "control loop" consisting of input, flow path, sensor, and controller has certain characteristics. Specifically, the unavoidable time delays in the loop establish a certain potential frequency of temperature oscillation for which the phase change around the loop is 2 π. If at this frequency the gain around the loop is greater than 1, sustained oscillations will occur (3).

An on-off controller always gives the undesired sustained temperature-oscillations just described. In order to get rid of this undesired "hunting", some form of proportional control must be used. In proportional control the power has a certain value when the sensor is at the desired temperature. If the sensor departs by, say, 5 mdeg from the desired temperature, the power is changed by a certain amount. If the amount of departure increases to 10 mdeg, the change in power is doubled, remaining proportional to the departure throughout a range of temperatures known as the "proportional band."

The gain around the control loop of a proportional controller may be varied by changing the constant of proportionality of the controller. This constant, dW/dT, is the rate of change of average power input W with departure from the desired temperature T. For the most accurate temperature control this constant (it is negative) should be increased in absolute value until the loop gain approaches 1. If the gain exceeds 1, hunting will persist. But with a gain less than 1 no spontaneous oscillations will occur, and the results of accidental disturbances will be damped out.

In the apparatus now being described, proportional control is obtained not by continuous adjustment of the power but by an alternation between two levels of power, the alternations being sufficiently rapid so that the temperature does not appreciably follow the alternations. If the temperature is at the desired value, the alternating periods of lower and higher power are of approximately equal length. If the temperature is, for example, too high, the periods of higher power are shortened and the periods of lower power are correspondingly lengthened. This decreases the average power and brings the temperature back to the desired value. The division of time between the periods of higher power and the periods of lower power is continuously variable, and hence the average power is continuously variable between the two established levels.

The alternations between the two established power levels are obtained by the use of a special oscillator that generates a sinusoidal emf having a frequency of about 1/5 cycle per second. The mean value of this emf is zero; hence it can be added to the control signal initiated by the thermopile without displacing the control-point temperature.

The addition of the two signals is accomplished in a magnetic amplifier having two control windings. One winding receives the control signal from the thermopile, after it has been amplified by the null detector. The other winding receives the sinusoidal emf from the special oscillator. The magnetic amplifier responds to the vector sum of the two inputs, and its output causes a built-in relay to open or close.

When the emf generated by the thermopile is zero, the only input to the magnetic amplifier comes from the special oscillator. This sinusoidal input causes the relay of the magnetic amplifier to open and close with a period of about 5 seconds, the "open" and "closed" fractions of the period each being about 2.5 seconds long. When the error signal from the thermopile is not zero, the distribution of total time between "open" and "closed" fractions is modified as described above.

The two power levels are established by suitable manual adjustment of the resistances that are in series with the guard-ring heater. One of these resistances is periodically shorted and restored to the circuit by the action of the magnetic-amplifier-relay combination. The magnitude of this resistance is adjustable, as described more fully below. The constant of proportionality dW/dT is increased in magnitude by increasing this resistance.

The method described above for obtaining a continuously-variable average power input by relatively rapid alternations between two fixed power levels is a variation of the method that appears to have been first used by Gouy (4) in 1897. It was used by Sligh (5) in 1920 and is now widely used in industrial practice, but seems to be less well known to scientists than to control engineers.

3. Details of Construction

Null Detector. The detector is a Brown Electronik Model 104 W1G. Its rated sensitivity is a meter deflection of 1 mm for an input of 1 microvolt. The meter has a zero-center scale and is protected against overload by a double-diode limiter. When automatic control is used, one of the 2500-ohm windings of the magnetic amplifier is connected in series with the meter.

Magnetic Amplifier and Relay. The magnetic amplifier and relay is a combination unit, Sigma Model 8205K3P-93270 (2500/2500-DA). It has two control windings of 2500 ohms each and actuates two separate relays, only one of which was used in the present work. The relay was used to drive another heavier relay. The Sigma relay is rated to operate on a change in input of 0.2 microwatt; this sensitivity

has been more than adequate for our needs. Control winding No. 1 receives the oscillating signal from the Wien-bridge oscillator. Control winding No. 2 receives the signal from the null-detector output. Relay RA is not used; relay RB controls the power to the guard ring. The sensitivity control is set at maximum. A microammeter (50-0-50 microamperes) permits the input to either control winding to be observed. A selector switch inserts the meter in either of the two circuits. The switch has an "off" position in which both circuits are open. This is used when manual control is desired.

Power Levels. As stated earlier, the difference between the high power and low power levels depends on the magnitude of the resistance that is periodically shorted out and restored to the circuit. A switch, mounted on the panel of the oscillator chassis, permits this resistance to be given any of the following values: 0.1, 0.3, 0.4, 0.5, 1, 10, or 100 ohms. The higher values give large changes in power level, and are used much less than the lower values. In general the highest values make the gain around the control loop greater than unity and lead to sustained temperature oscillations. The lowest values give very little latitude for change in power demand, and when they are used temperature control is lost rather easily. A resistance equal to about 1 percent of the total circuit resistance is about right. When this resistance is shorted by the relay, the current is increased by about 1 percent, and the power supplied to the guard ring is increased by about 2 percent.

Wien-Bridge Oscillator. The circuit of the Wien-bridge oscillator is shown in Figure 2. The unusual feature of this oscillator is the very low frequency required of it. As shown in the figure, a Wien bridge contains capacitors in two adjacent arms. One is in series with a resistance; the other is in parallel with a resistance. The bridge can be balanced only at one particular frequency, which is determined by the two bridge arms containing the capacitors. This frequency is given by

$$\omega = (R_3 R_4 C_3 C_4)^{-\frac{1}{2}},$$

the bridge arms being numbered as in Figure 2, and ω being the angular frequency $2\pi\nu$. The remaining bridge arms, R_1 and R_2, are

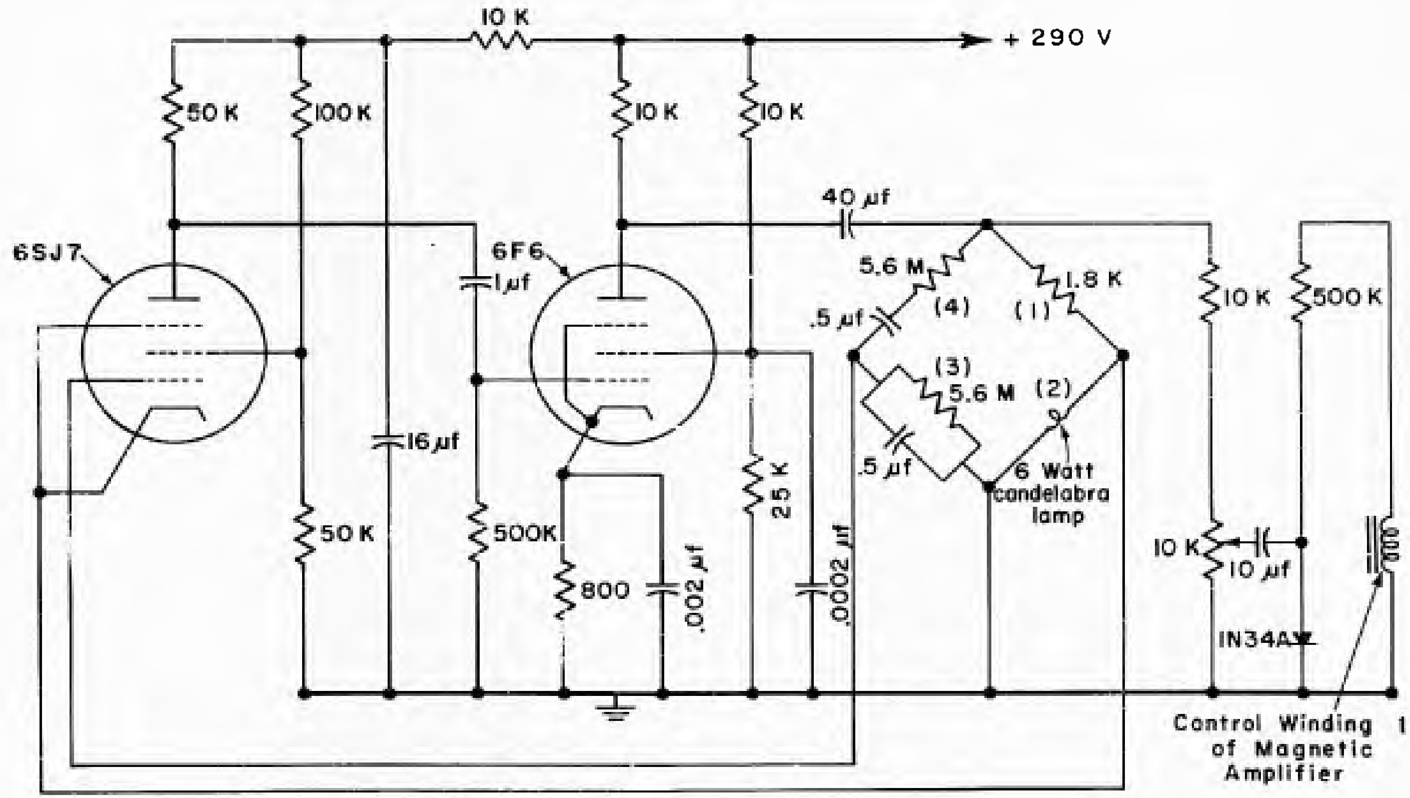

Figure 2. Circuit of the Wien-Bridge oscillator. The frequency is about 1/5 cycle per second and the output is fed to one of the two input windings of the magnetic amplifier.

purely resistive. At balance they must satisfy the relationship

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} + \frac{C_3}{C_4},$$

but they do not enter into the expression for the frequency at balance.

The oscillator operates because of controlled feedback supplied through the bridge. In normal operation the bridge is slightly out of balance so that a suitable signal is fed back to the 6SJ7 tube. Amplitude of the oscillations is limited by bridge arm 2, which is a 6-watt candelabra lamp.

The oscillator of Figure 2 operated at a frequency of about 1/5 cycle per second, whereas the computed frequency at which the Wien bridge would be in balance is about 1/18 cycle per second. The cause of the discrepancy is not definitely known, but it is clear that a bridge containing 5.6-megohm resistors will be seriously affected by any leakage currents in the capacitors, and will be easily unbalanced if any grid current is drawn by the 6SJ7 tube. In this connection it should be noted that the recommended maximum grid resistance of this tube is 1 megohm. The grid resistance in the circuit of Figure 2 is principally determined by the bridge arm consisting of 0.5 µf in parallel with 5.6 megohms. This impedance is higher than the recommended maximum.

Paper capacitors are used in the bridge, since electrolytic capacitors have too much leakage current. If it were not for the inconvenience of using large-size paper capacitors, these would have been increased above 0.5 µf and the 5.6 megohm resistors reduced in size, but so far the performance of the present system has been adequate.

With the 10,000-ohm output-control potentiometer set at maximum, the current through the control winding No. 1 of the magnetic amplifier varies periodically between the limits of 0 and 13 microamperes. Because of the clamping circuit containing the 1N34A diode, the direction of current flow never changes. This prevents the unused relay contacts of the magnetic amplifier from opening and closing with the oscillator cycle. (Contacts RA and RB do not open and close simultaneously. One set has its highest sensitivity for current of one direction, and the other its highest sensitivity for current of

the opposite direction.) It also causes a displacement of the balance point of the controller.

Displacement of the balance point might be expected to be a disadvantage, but because of the nature of the response of the magnetic amplifier and relay, the displacement is actually desirable and tends to make the "on" and "off" periods equal when the error signal from the thermopile is zero. Fine adjustment in this respect is obtained by offsetting the zero adjuster of the null detector.

A conventional full-wave filtered power supply furnishes power to the tube filaments, screens, and plates, and to the indicator lamp.

Galvanometer. A moving-coil galvanometer, Leeds and Northrup Model 2430-A, was at all times connected in parallel with the Electronik null detector, for observation of the output of the 6-power thermopile. The galvanometer was somewhat more sensitive than the detector, but its principal purpose was to monitor zero-drift. The open-circuit zero of the galvanometer was quite stable. This zero is observed once or twice during each period when accurate thermal-conductivity measurements are being made on a sample. It is possible that the galvanometer could be dispensed with and the null detector used to determine the point at which the thermocouple output is zero.

4. Operating Procedure

The following instructions are illustrative, intended primarily for one who has not operated the controller before. Deviations from the ten steps listed below will be made by experienced operators when the situation so demands.

1. See that the galvanometers are so heavily shunted as to greatly reduce their sensitivity. Set the control resistor of the automatic control circuit to its lowest value (0.1 ohm).

2. Turn on all the power circuits. This includes the DC supply (Nobatron), the top-shield heater (AC), and the water bath thermoregulator. The null detector should be turned on at this time so that it can warm up and stabilize. Finally, after the Nobatron has warmed up for about a minute, the hot-plate and guard-ring circuits should be closed. The sum of hot-plate and guard-ring

currents can be as high as 1 ampere and probably higher, but should not exceed say, 1.25 amperes, unless time is more important than a possible burnout. The top-shield power should be adjusted so that the top shield heats as fast as, or somewhat faster than, the hot plate and guard ring. Automatic control is not used while the heating is started.

3. As the desired operating temperature is approached, the power to the magnetic amplifier is turned on. This causes the control relay to close if the guard ring is colder than the hot plate, but has little effect on the heating rate because the control resistor is small. As the temperature comes closer to the operating point, the control resistor is increased to its largest value (100 ohms). Then the hot-plate power is reduced. As soon as the guard ring goes above the temperature of the hot plate, the relay opens and the guard-ring power is also reduced. The top-shield power must be reduced manually.

4. The hot plate is brought to the desired temperature, the guard ring and top shield being suitably controlled so that they follow the temperature of the hot plate. As soon as practicable, the automatic-control resistor is reduced from 100 to 10 ohms and then to 1 ohm, the other resistance in the circuit being increased as necessary. The shunt on the galvanometer null-detector combination is removed when the temperature difference between hot plate and guard ring becomes small enough.

5. At this point the oscillator of the automatic controller is turned on (the tubes light), and the signal from the oscillator is applied to the magnetic amplifier, along with the signal from the null detector. The oscillator output should be set at maximum. When the guard-ring temperature is brought sufficiently close to the hot-plate temperature, the oscillator signal can override any signal from the null detector, and the control relay starts opening and closing regularly with a period of about 5 seconds. The average guard-ring current is adjusted so that the relay is closed for approximately half the period and open for the other half.

6. While step 5 is being taken the top shield is brought to the temperature of the guard ring and hot plate, and the shunt on the top-shield galvanometer is removed.

7. The apparatus is allowed to stabilize for perhaps 10 minutes. The automatic controller does not control the temperature of the hot plate but simply keeps the guard ring at the same temperature as the hot plate. Hence the hot plate temperature must be monitored by observing the emf generated by the thermocouples with which the temperature difference across the sample is measured. The hot-plate power is adjusted to hold this temperature difference at the desired value. When the period of relatively rapid change in power requirements is over, the automatic-control resistance is reduced from 1 ohm to 1/2 ohm or lower and the resistance in the rest of the circuit is increased as necessary to keep the average power input constant.

8. At this time the zero of the guard-ring galvanometer should be checked by opening the circuit to it (but without opening the circuit to the null-detector input). The mechanical zero is adjusted to some desired position on the scale and the circuit closed again. It will generally be found that the automatic controller is holding the guard ring at a temperature slightly off balance, as indicated by the galvanometer. The zero adjustment of the null detector is now moved, a little at a time, until the galvanometer is brought to its mechanical zero.

9. Adjustments of the top-shield and hot-plate power inputs are continued to maintain the desired operating conditions. The guard-ring power is adjusted occasionally if the "on" periods and "off" periods become seriously unequal (if one becomes double the other, for example). If this last adjustment is neglected, the relay will stay either open or closed continuously, depending on whether the guard ring is warmer or cooler than the hot plate. The temperature has gone outside the "proportional band" and the benefit of the oscillator signal is lost.

10. About 3 hours after the run is started, the adjustment of hot-plate power should be discontinued, unless the adjustment is made for the specific purpose of restoring the power to the desired value. If this is not done it will be difficult to tell when the steady state of heat flow within the sample has been reached. The rating period, which begins when hot-plate power adjustments are discontinued, is described in the preceding report of the series (1).

One modification in operating procedure that is sometimes helpful relates to step 4. Rather than bring the apparatus to the desired value of temperature difference across the sample and hold it there, the temperature difference may be brought to a value too large by, say, 6 percent. This too-large difference may be maintained for about 45 minutes and then dropped to the desired value. Such a procedure appears to cause a more rapid approach to the steady state but no quantitative data on this point are available. The program that gives the most rapid approach to the steady state was not determined. It will vary with the nature and thickness of the sample.

5. Performance

The automatic control reduces the difficult parts of a run from a two-man job to a one-man job. Further, the one man has considerable free time in which to calculate data while a run is in progress. He would not have this free time if complete manual control were used.

The automatic control is more accurate than manual control. During a rating period, the oscillations of the guard-ring galvanometer, in response to the opening and closing of the controller relay, are seldom as large as ± 1 mm, which is equivalent to an emf oscillation of ± 0.5 microvolts, which in turn is equivalent to a temperature oscillation of ± 2 mdeg C. Under the best conditions, motion of the galvanometer spot is hardly noticeable, and the temperature oscillations do not exceed 0.5 millidegrees. With the automatic controller, the time integral of the excursions is substantially zero, the negative excursions being equal to the positive ones. With manual control, the operator is not likely to achieve such a good balance between "hot" and "cold" excursions.

A second automatic controller, to keep the top shield automatically at the right temperature, would be desirable. However, this control is much less important than the guard-ring control. Further, the top shield is easier to control when the guard ring is automatically controlled than when everything is done manually.

6. Acknowledgment

The authors acknowledge the assistance of Dr. Harold J. Hoge, of the Thermodynamics Laboratory, Pioneering Research Division, who coordinated all of the work described in the group of three reports now being issued.

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